Institution: University of York

Unit of Assessment: 9, Physics

Title of case study: Contributions to the Orion project

1. Summary of the impact (indicative maximum 100 words)

The development by Tallents et al of a new plasma opacity measurement technique contributed to the decision by the UK Ministry of Defence (MoD) to construct the £150 million Orion laser at the Atomic Weapons Laboratory (AWE) for the measurement of material properties at high energy density. Orion will enable AWE to measure e.g. opacities important in nuclear weapons design without underground tests and at much lower cost than would have been the case if it had followed the French and US programmes with lasers costing over £1 billion.

2. Underpinning research (indicative maximum 500 words)

A series of papers [1, 2] co-authored by Tallents demonstrated a new technique for the measurement of plasma opacity. The technique relies on 'Kirchhoff's law' relating emissivity to absorption for material in thermal equilibrium. High power short pulse lasers were used to heat a target comprising a thin layer of high *Z* material covered in plastic and the emission from the 'buried layer' recorded using a spectrometer. The populations of quantum states were in local thermal equilibrium (LTE) as the material was heated to temperatures > 100 eV before expansion lowered the material density significantly below the solid value. Consequently, a hot (>100 eV), dense ($\approx$ 1 gcm^{-3}) plasma was formed which emitted over a short ($\approx$ 1 ps) duration. From the emission, the plasma opacity was evaluated using Kirchhoff's law. Papers [1, 2] are published in specialist international peer review journals often used for publicising high energy density plasma and radiative transfer results.

The Kirchhoff's law method of opacity evaluation has been used to benchmark opacity codes. Revisions to opacity codes led to more accurate opacities used in astrophysics research and by AWE. The new technique has advantages over the previously utilised opacity measurement method (where another laser plasma x-ray emission 'backlights' a plasma so that the radiation transmission and hence opacity are measured). These advantages are: (1) thin layers of material sandwiched in low *Z* material can be used so that the plasma is uniform and at high density (greater than solid density has been achieved), (2) the opacity of plasma at high temperature (up to 1 keV) can be measured (with the backlighter method, temperatures are limited by the achievable backlighter temperature).

The York Plasma and Fusion group have strongly contributed to more recent opacity research utilising four EPSRC research grants [6]. These grants further developed opacity measurement techniques whereby plasma-based extreme ultra violet (EUV) lasers were used to probe high density, high temperature plasmas created by synchronised optical laser irradiation of solid targets [4]. The opacity target design here is similar to the targets utilised for the Kirchhoff's law opacity measurements, but opacity is measured from the transmission of the EUV laser through the target after laser heating. Some of the advantages of the Kirchhoff's law method of opacity measurements are preserved (e.g. thin tamped layers of material are studied so that the plasma is dense and uniform), but the technique does not require LTE and spectral resolution at the EUV laser wavelength is improved by up to two orders-of-magnitude. The brightness of the EUV laser ensures that that the opacity of hot plasma (up to 1 keV) can be measured.

A detailed line accounting opacity code has been developed at York with opacity predictions compared to measurements of EUV laser transmission and earlier opacity measurements important for the revision of the Cepheid variable opacities [4]. Work has expanded to consider opacity measurements with low energy laser systems and with free-electron lasers [5].

An experiment to develop the Kirchhoff's law method of opacity determination was scheduled via a

Central Laser Facility, Rutherford Appleton Laboratory experiment obtained following an application for access from Professor Tallents. Tallents led the experimental team and the experimental time was allocated to him as PI. Steven Rose now at Imperial College led the theoretical opacity modelling for the experiment. The results from the experiment were analysed over a number of years. Evidence for the developing interest of AWE in the technique can be found in reference [2] where Davidson and Nazir are AWE employees and Tallents and his students, Smith and Pestehe are co-authors. Tallents and student Pestehe moved to York in 1999 and Tallents further developed the collaboration with AWE on opacity measurements with a series of opacity-oriented grants [6]. The work at AWE is now led by Dr David Hoarty. AWE experimental work continued on the technique at the Central Laser Facility (CLF) during 2010 while the Helen laser was decommissioned. The Orion laser was commissioned in 2013 with a milestone experiment utilising the technique.

3. References to the research (indicative maximum of six references)

[1] R Smith, G J Tallents, S J Pestehe, G Hirst, J Lin, S Rose and M Tagviashvili 1999 Laser and Particle beams **17**, 477-485. ‘A spectroscopic analysis of near solid density plasmas’. [Conference report]

[2] S J Davidson, K Nazir, S J Rose, R Smith and G J Tallents 2000 JQSRT **65**, 151-160. ‘Short pulse laser opacity measurements’. DOI: 10.1016/S0022-4073(99)00063-1 [9 citations]

[3] M H Edwards, D Whittaker, P Mistry, N Booth, G J Pert G J Tallents et al 2006 Phys. Rev. Lett. **97**, 03500*.* ‘Opacity measurements of a hot iron plasma using an x-ray laser’. DOI: 10.1103/PhysRevLett.97.035001 [21 citations].

[4] D S Whittaker and G J Tallents 2009 Mon. Note R. Astr. Soc. ‘Iron opacity predictions under solar interior conditions’. DOI: 10.1111/j.1365-2966.2009.15523.x [5 citations]

[5] D W Whittaker, E Wagenaars, G J Tallents 2011 Physics of Plasmas **18**, 013105 ‘Temperatures following x-ray free-electron-laser (XFEL) heating of thin low- and medium-Z solid targets’. DOI: 10.1063/1.3546031 [4 citations]

[6] ‘Opacity measurements at extreme ultra-violet wavelengths’ [EPSRC PI Tallents £407481, 2004 - 2007],
‘Laboratory measurements of the opacity of solar plasmas’ [EPSRC PI Tallents £832439, 2007 - 2011],
‘Next generation application of EUV lasers’ [EPSRC PI Tallents £120554 2007 - 2011].
‘Plasmas created by extreme ultraviolet lasers’ [EPSRC PI £425,431 2013 – 2015].

Citation data taken from Scopus, 14/11/2013
Publications without a DOI are available on request

4. Details of the impact (indicative maximum 750 words)

A new method of plasma opacity measurement developed by Professor Greg Tallents in collaboration with AWE from 1999 plays a key role in the secure storage and maintenance of nuclear weapons by the UK Atomic Weapons Establishment (AWE). The method has meant that experimental stockpile stewardship programmes relevant to opacity without underground testing can be undertaken in the UK using large laboratory lasers. Experiments by AWE on the Helen laser up to 2010, and more recently on the newly constructed Orion laser, have shown that weapons-relevant densities and temperatures can be reached and accurately diagnosed using these techniques.

The Orion laser system at AWE (costing £150m) is now complete. The Orion laser was specifically designed to facilitate opacity experiments using the technique. The first plasma experiment using this new laser was a milestone opacity measurement (at specified density 4 gcm^{-3}) using the technique of this impact. Though details are obviously classified and not published (for example, in order to make the proliferation of weapons to new states or groups more difficult), it can be surmised that the opacity of hot plasma is important in controlling energy flow during weapon detonation and other aspects of nuclear weapons design. The new opacity measurement technique is consequently helping AWE to ensure the safe stockpiling of nuclear weapons without underground testing and without the need to construct a £1bn laser, as is being developed by France and the US for stockpile stewardship.

An acknowledgement of the pivotal nature of the Kirchhoff's law opacity work in plasma opacity work has been presented in a refereed publication [S J Rose 2005 Plasma Phys. Control Fusion **47**, B735 'New experimental possibilities for measuring radiative opacity under conditions in the Sun's interior'] The critical role of opacity in nuclear weapons design is described in a 2002 open publication by the Ministry of Defence Chief Scientific Advisor, [K O'Nions, R Pitman and C Marsh 2002 Nature **415**, 853. 'Science of nuclear warheads'.].

Since 2008, AWE effort has increasingly sought to make opacity measurement using the 'Kirchhoff's law' technique by using the AWE Helen laser (up to 2010), paying for laser time at the Rutherford Appleton Laboratory Central Laser Facility and by the construction of the £150m Orion laser at the AWE site Aldermaston. The Kirchhoff's law opacity measuring technique for aluminium compressed to 4 gcm^{-3} using shocks resulting from longer pulse lasers (to produce high density) and a short pulse, high irradiance laser (for heating) was demonstrated on the Orion laser in early 2013. This was the final commissioning test of the new laser necessary to satisfy AWE contract obligations to the MoD. A York PhD graduate supervised by Tallents (Lauren Hobbs – nee Gartside) took up a staff position at AWE in 2011 in order to work on the opacity programme under the supervision of Dr David Hoarty and contributed significantly to the opacity milestone experiment using the 'Kirchhoff's law' technique. Hobbs presented the AWE milestone results for the first time at the Institute of physics Annual Plasma Physics Conference in March 2013 in York.

The US stockpile stewardship programme has recognised the success of the UK approach and US experiments using the technique developed by Tallents are now being developed and undertaken on the COMET laser at Lawrence Livermore National Laboratory (LLNL) and in collaboration with AWE on the Orion laser. A student of Tallents (Mohammed Shahzad half-funded by AWE) took part in a 4-week opacity experiment at LLNL on the COMET laser in November/December 2012. Former student Lauren Hobbs (mentioned above) is also involved in the work at LLNL. In 2013, a student fully-funded by AWE (Valentiin Aslanyan) developed simulation results showing that the solid density plasmas produced in buried layer experiments such as undertaken on the Orion laser, can be modelled accurately assuming local thermodynamic equilibrium (LTE) as the times for populations of moderate-*Z* material to equilibrate are of order 10 – 50 fs.

Dr Tim Goldsack from AWE provided the following statement in relation to this impact on 27th September 2013.

"Under the Comprehensive Test-Ban Treaty, AWE's task of stockpile stewardship is challenging. In order to gain a deeper understanding of nuclear-weapon physics for stewardship without underground nuclear tests it is necessary to be able to create, and accurately diagnose, hot dense plasmas. It had been thought that very large lasers (I.e. comparable in performance - and hence cost - to the National Ignition Facility at LLNL etc) would be needed. Prof. Tallents papers helped give rise to the idea that a smaller (and hence significantly less expensive to build and operate) laser, incorporating both long- and short-pulse beams could allow researchers to gain access to hot, dense plasmas at lower cost, and, indeed, open up other interesting and relevant areas of so-called "high-energy-density" physics. This realisation led to the construction of the Orion laser at AWE. Orion is currently being commissioned, but already early test shots have shown the great promise of this approach, with high temperatures ($\approx$ 600 eV) being achieved at greater than solid density. There is a full programme of work planned for Orion, starting in April 2013 when commissioning is completed, and AWE is delighted to acknowledge the significant contributions Prof Tallents has made.

It is also worth noting that AWE looks to the York Plasma Group for potential recruits to the AWE Plasma Group, and recruited one recently."

5. Sources to corroborate the impact (indicative maximum of 10 references)

Letter, Group Leader, Plasma Physics, AWE

Letter: Head of Profession for Physics, AWE